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TIII

Influence of a gravitationally induced phase on neutrino oscillation and Baryogenesis

Sara Krieg

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Summer School Erice

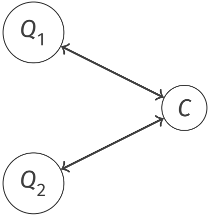
Outline

- Motivation
- Basics
- Phase shift of neutrino oscillation due to entanglement
- Baryogenesis via neutrino oscillation

Motivation

- No uncontroversial proposal for quantum gravity
  - Applying a quantization to the gravitational field
  - String theory?
- Does gravity have to be quantized at all?
- Today's ideas leads to non-testable predictions
- Experimental evidence that gravitational field has quantum properties?

Basics: entanglement as a hint for quantum effects - Thought Experiment



- If two Systems get entangled due to interaction with mediator →Mediator has to be quantum!
  Nachweis
- Now: Gravitational interaction of two heavy, sterile neutrinos in the early universe!
- Interaction should change phase in transition probability
- ”Witness of entanglement”
- Evidence for quantum gravity effects in neutrino oscillation?

General transition probabilities of neutrino oscillation

- For one neutrino

$$P_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{A>B} \mathrm{Re}\left(U^*_{\alpha A}U_{\beta A}U_{\alpha B}U^*_{\beta B}\right)\sin^2\left((E_A - E_B)\frac{t}{2}\right) + 2\sum_{A>B} \mathrm{Im}\left(U^*_{\alpha A}U_{\beta A}U_{\alpha B}U^*_{\beta B}\right)\sin\left((E_A - E_B)\,t\right)$$

- For one neutrino in gravitational interaction with a neutrino background

$$\bar{P}_{\alpha\to\beta} = \delta_{\alpha\beta} - 4\sum_{A>C} \mathrm{Re}\left(U^*_{\alpha A}U_{\alpha C}U_{\beta A}U^*_{\beta C}\right)\sum_B p_B \sin^2\left(\Delta\epsilon^{BB}_{AC}\frac{t}{2}\right) + 2\sum_{A>C} \mathrm{Im}\left(U^*_{\alpha A}U_{\alpha C}U_{\beta A}U^*_{\beta C}\right)\sum_B p_B \sin\left(\Delta\epsilon^{BB}_{AC}t\right)$$

- P_B: Probability that mass eigenstate B occurs in background
- Energy eigenvalue differences:

$$\Delta\epsilon^{BB}_{AC} = \epsilon^B_A - \epsilon^B_C = E^{(1)}_A + E^{(2)}_B - \frac{G}{d}m_A m_B - E^{(1)}_C - E^{(2)}_B + \frac{G}{d}m_C m_B$$

How large can the effect be? - Determination of the distance

- Motivation: Distance between neutrinos needs to make sense
- Neutrinos of type A and B →Boltzmann distribution

$$d = \left(\frac{1}{e^{-\frac{m_A}{T}} \left(\frac{m_A T}{2\pi}\right)^{\frac{3}{2}} + e^{-\frac{m_B T}{2\pi}} \left(\frac{m_B T}{2\pi}\right)^{\frac{3}{2}}} \right)^{\frac{1}{3}}$$

- For large effects →Smallest possible distance (Choose Δm_{AC} accordingly)
- Minimal distance at $\Delta m_{AC} \approx \frac{3}{2} T + m_A$
- →Choose large temperature where neutrinos get produced

$$T = 1 \times 10^{16} \mathrm{GeV}$$

$$d = 2.68 \times 10^{-25} \mathrm{eV}^{-1}$$

Transition Probability for two flavours

- For one neutrino (Assuming a non rel. approximation)

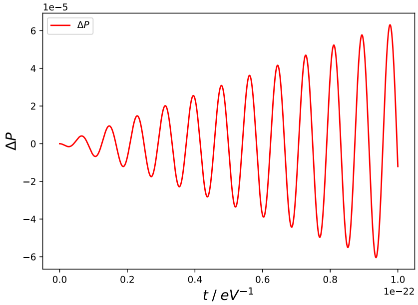
$$P_{\alpha\to\alpha} = 1 - \sin^2(2\Theta)\sin^2\left(\left(\Delta m_{21} - \frac{p_1^2 \Delta m_{21}}{2m_2 m_1}\right)\frac{t}{2}\right)$$

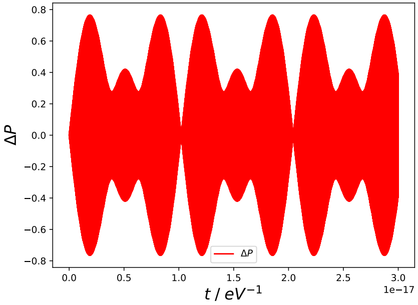
- For one neutrino in gravitational interaction with a neutrino background

$$\bar{P}_{\alpha\to\alpha} = 1 - \frac{1}{2}\sin^2(2\Theta)\left[\sin^2\left(\left(\Delta m_{21} - \frac{p_1^2 \Delta m_{21}}{2m_2 m_1} - \frac{G}{d} m_1 \Delta m_{21}\right)\frac{t}{2}\right) + \sin^2\left(\left(\Delta m_{21} - \frac{p_1^2 \Delta m_{21}}{2m_2 m_1} - \frac{G}{d} m_2 \Delta m_{21}\right)\frac{t}{2}\right)\right]$$

Transition amplitude for two flavours

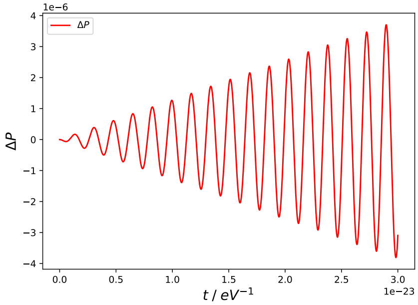
$$\Delta P = P_{\alpha\to\alpha} - \bar{P}_{\alpha\to\alpha}$$

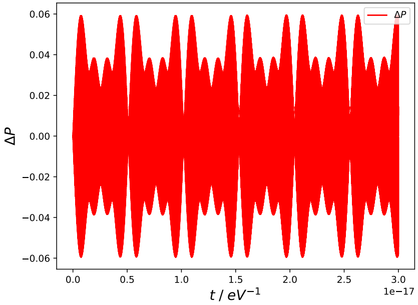




Transition amplitude for three flavours

$$\Delta P = P_{\alpha\to\alpha} - \bar{P}_{\alpha\to\alpha}$$





Difference of the transition probability

- Phase shift of transition probability due to gravitational interaction!
- Effects are very small but in principle measurable
- Influence on Baryogenesis?

Baryogenesis via neutrino oscillation

- Big question in particle physics: Origin of baryon asymmetry
- Popular: Origin from lepton asymmetry.
- One possibility: Baryogenesis via neutrino oscillation
  BaryomitNeutrinooszi
- Extension of SM by three types of Majorana neutrinos N_a with $a = A, B, C$
- Total Leptonnumber does not get broken

$$L^{\text{tot}} = L + L_A + L_B + L_C$$

- CP-Violation due to mixing in neutrino sector $\rightarrow L_A = L_B = L_C = 0$ developed to $L_A \neq 0$, $L_B \neq 0$, $L_C \neq 0$
- But still: $L^{tot} = 0$ $\rightarrow$Total lepton number is distributed differently among types

Baryogenesis via neutrino oscillation

- Lepton asymmetry is communicated to SM neutrinos via Yukawa interaction
- For this: Hierarchy. N_A and N_B in thermal equalibrium before t_{EW} $\rightarrow N_C$ afterwards
- Electroweak sphalerons process asymmetry into baryon asymmetry

  BaryomitNeutrinooszi

Baryogenesis via neutrino oscillation

- For one neutrino
  BaryomitNeutrinooszi

$$\Delta_L \approx J \sin(\Phi) h_{AB}^2 h_{AC}^2 h_{BC}^2 \cdot \left(\frac{M_{\mathrm{Pl}}^* \left(1 + \frac{M_{\mathrm{Pl}}^* \Delta m_{31}}{2 m_3 m_1}\right)}{\Delta m_{31}} \right)^{\frac{1}{2}} \left(\frac{M_{\mathrm{Pl}}^* \left(1 + \frac{M_{\mathrm{Pl}}^* \Delta m_{21}}{2 m_2 m_1}\right)}{\Delta m_{21}} \right)^{\frac{1}{2}} \left(\frac{M_{\mathrm{Pl}}^* \left(1 + \frac{M_{\mathrm{Pl}}^* \Delta m_{32}}{2 m_3 m_2}\right)}{\Delta m_{32}} \right)^{\frac{1}{2}}$$

- For two entangled neutrinos

$$\Delta_L \approx J \sin(\Phi) h_{AB}^2 h_{AC}^2 h_{BC}^2 \cdot \left(\frac{M_{\mathrm{Pl}}^* \left(1 + \frac{M_{\mathrm{Pl}}^* \Delta m_{31}}{2 m_3 m_1}\right)}{\Delta m_{31}\left(1 - \frac{G}{d}\bar{M}\right)} \right)^{\frac{1}{2}} \left(\frac{M_{\mathrm{Pl}}^* \left(1 + \frac{M_{\mathrm{Pl}}^* \Delta m_{21}}{2 m_2 m_1}\right)}{\Delta m_{21}\left(1 - \frac{G}{d}\bar{M}\right)} \right)^{\frac{1}{2}} \left(\frac{M_{\mathrm{Pl}}^* \left(1 + \frac{M_{\mathrm{Pl}}^* \Delta m_{32}}{2 m_3 m_2}\right)}{\Delta m_{32}\left(1 - \frac{G}{d}\bar{M}\right)} \right)^{\frac{1}{2}}$$

Baryogenesis via neutrino oscillation - Leptogenesis Temperature

- The distance has to be calculated at Leptogenesis Tempature

$$T_L = \left(\frac{M^*_{Pl} \Delta m_{AC} \left(1 - \frac{G}{d} \bar{M}\right)}{1 + \frac{M^*_{Pl} \Delta m_{AC}}{2 m_A m_C}} \right)$$

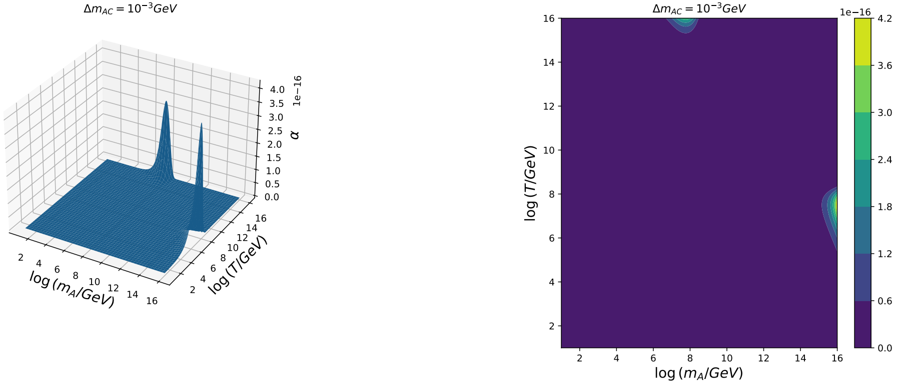
- Problem: T_L depends on d →Approximate the formula

$$\alpha = \frac{G}{d} \bar{M}$$

- α can take values between 1 and 0.

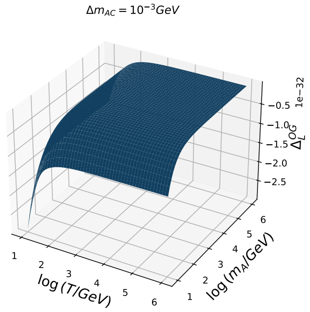
Baryogenesis via neutrino oscillation - Leptogenesis Temperature

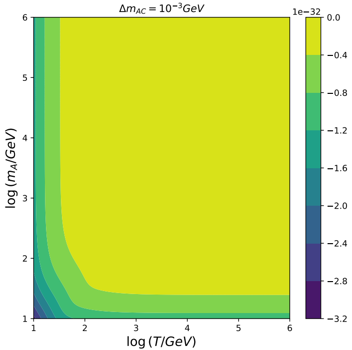
- Can $\alpha = \frac{G}{d}\bar{M}$ be neglected? →Solve numerically and plot!



Baryogenesis via neutrino oscillation

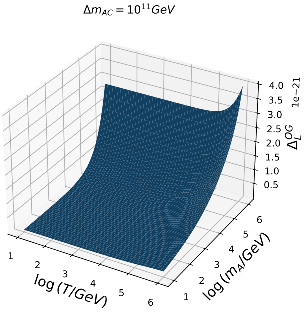
Difference between the Baryoasymmetries: $\Delta_L^{Diff} \approx -\frac{3}{2}\alpha\Delta_L^{OG}$

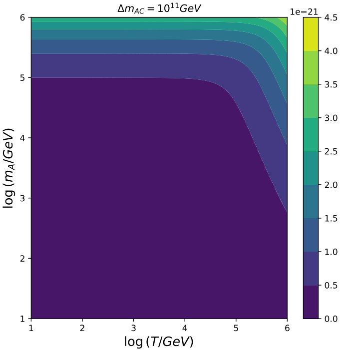




Baryogenesis via neutrino oscillation

Relative difference between the Baryoasymmetries: $\Delta_L^{rel} \approx \frac{3}{2}\alpha$





Summary and Outlook

- Influence of neutrino oscillation through gravitationally induced phase
- If phase is experimentally detectable →Confirmation of quantum gravity
- Very little effect on baryogenesis
- To be studied: Effect of a reduced Planck sclae (i.e. large G), e.g. in theories with large extra dimensions - Sizable effects possible?
- Always assumed equally distributed neutrino background →Would something change?
- Comparison with experimental data